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ACOUSTIC ABSORPTION COEFFICIENTS OF HUMAN BODY SURFACES

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(Prepared under Contract No. AF 33(616)-2770
by
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NOTICES

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FOREWORD

The research described in this report was performed by Dr. Eugene Ackerman, Pennsylvania State University, University Park, Penn., between 1956 and 1958, under Contract AF 33(616)-2770 and in support of Project No. 7210, "Acoustic Energy Control." The report is published under Project No. 7231, Biomechanics of Aerospace Operations," and Task No. 723103, "Biological Acoustics in Aerospace Environments." Dr. Henning E. von Gierke, Chief, Bioacoustics Branch, Biomedical Laboratory, 6570th Aerospace Medical Research Laboratories, was the project monitor.

Mr. Joseph Hsu, Mrs. Suzanna Marley, Mr. Arthur Jordan, Mrs. Joan Keener, and Mr. James Rupp are acknowledged for gathering data, and constructing and maintaining the equipment. Also, the help and advice of Dr. Robert L. Berger, Dr. Angelo J. Campanella, Dr. Adam Anthony (who reviewed the report) and Mr. Robert W. Farwell of Pennsylvania State University, and Dr. E. Franke* and Dr. H.L. Oestreicher, Biomedical Laboratory is acknowledged.

*Dr. E. Franke is now with the University of Cincinnati, Cincinnati, Ohio.

ABSTRACT

Reverberation chamber decay times were measured with and without human body surfaces exposed to the sound field. From these measurements acoustic absorption coefficients were computed for human body surfaces. These were all small compared to similar coefficients for laboratory animals. Typical values for the absorption coefficients measured for human body surfaces were in the range of 1 to 2 percent. Little variation was found from 1 to 20 kc. Measurements were not made outside of these limits. The results are discussed and compared with other values obtained by different methods.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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SECTION I

INTRODUCTION

The noise levels to which men are exposed have been steadily increasing. The sound pressure levels where people work and live have climbed continuously for the last 50 years; there is nothing to indicate that more and more men will not be exposed to higher and higher levels. Almost all agree that these high sound pressure levels are unpleasant, but most data indicate that high sound pressure levels are not harmful to humans. Exposure to high sound pressure levels may result in direct auditory effects, indirect effects of auditory stimulation, or nonauditory effects. This report deals only with nonauditory effects.

It would be of value to determine the amount of acoustical energy absorbed by the surface of man and animals (i.e., nonauditory effects). Some of the dramatic effects observed on small laboratory animals (rats, mice), such as whole body heating, have been explained and quantified on the basis of such absorption measurements (refs. 1, 2). The data accumulated by various methods of measurements on the percent of incident energy absorbed by laboratory animals have been reviewed.

On human subjects, so far only absorption measurements of relatively small areas of the body surface have been made (refs. 3, 4). These data have been used to estimate the total acoustic energy absorbed, but the limitations of extrapolating from small body areas to whole limbs or the whole body are obvious. Therefore, the purpose of the work reported in this paper was to measure the acoustic absorption of larger areas and body parts of the unclothed human body. These measurements were made in the frequency range of 1 to 20 kc. From the low value of the absorption coefficient we measured, severe heating phenomena probably will not occur even at intensities existing in the neighborhood of jet airplanes, provided energy in the higher regions of the spectrum is not important. However, our data do indicate that a slow, but definite, heating might occur at sound pressure levels over the whole body of about 170 db in this frequency range. Local heating damage might even occur at sound pressure levels of about 165 db. This heating problem is discussed in the appendix of a report (ref. 2) where similar conclusions are suggested.

The importance of the high frequency regions of the spectrum should be emphasized. Although the level per cycle in this region may be lower, the overall power may be comparable. Thus, if the absorption coefficients in the high frequency region were to rise, this frequency range might be the only important one as far as energy actually absorbed. For this reason, it appears particularly important to know the absorption coefficient at all frequency ranges within which a jet engine noise or factory noise has an appreciable component.

Knowing the absorption coefficients is not sufficient to really predict the heating or other damage which may result. It is necessary also to know how the energy is distributed once it is within the body and where it is absorbed. Thus we

have measured acoustic absorption coefficients that are presented as empirical measurements. In the discussion, we have extrapolated other measurements to make an interpretation of our absorption coefficients possible.

The measurements reported in the following sections are based on a reverberation chamber technique. Here the decay time of a noise in a reverberation cham- is measured with a human hand or human limb inserted, or a human palm covering an opening in the chamber. The decay time is then remeasured with the chamber completely sealed. The difference in the decay time allows one to compute the absorption coefficient for the human body surface. The absorption of the chamber wall will be shown to be not negligible and therefore must be included in the calculations.

A more direct approach to the problem would be to place a person in a very intense sound field and observe the heat changes which occur. This approach is discussed in more detail for mice in a previous report (ref. 1).

Other approaches (refs. 2, 3, 4, 5, 6, 7), still less direct, have been used to measure the absorption coefficients of human surfaces. Essentially, the methods discussed in these reports consist of placing a rod or tube against an area of the skin and measuring the effective absorption of normal waves. These measurements showed that at very low frequencies pronounced surface waves are set up. As the frequency is raised, the effective normal acoustic absorption coefficient dropped for any given area. However, the absorption coefficient also dropped as larger and larger areas were used. The interpretation of this material (discussed in Sections II and V) indicates that surface or shear waves contribute strongly to the absorption coefficient in all cases. With this interpretation, the drop in the normal absorption coefficient with increased frequency and the contrasting constant values obtained in the reverberation chamber can be reconciled.

This overall picture is presented in Section VI, which includes the discussion and conclusions. These are based on the data in Sections IV and V, which were obtained with the equipment described in Section III. The symbols used and the pertenent theory are reviewed in Section II.

SECTION II

SYMBOLS AND THEORY

A. Symbols

a	absorption cross-section
α	absorption coefficient in percent
p	pressure in μ bars
c	wave velocity
ρ	density
z	specific acoustic impedance

ζ	impedance ratio
ζ_o	normalized impedance ratio
t	time
τ	reverberation time
L	sound pressure level in db re 2×10^{-4} μ bars
A	area
V	volume
v	frequency

B. Theory

As noted in our previous report (ref. 1), the acoustic absorption cross-section (or absorption) for an object in air is equal to the power absorbed divided by the incident free field intensity. This absorption is denoted by the symbol a. Often it is more convenient to discuss the ration of a to the actual surface area A. The ratio

$$\alpha = \frac{a}{A} \times 100$$

is called the absorption coefficient; it is measured in percent. This acoustic absorption coefficient depends on a number of factors including: the frequency , v ; the ratio, ζ_o , of the specific acoustic impedance of the object, z , to the characteristic impedance of air $(\rho c)_o$ defined by

$$\zeta_o = z/(\rho c)_o;$$

the shape of the object, and the shape of the incident waves.

For the case of normal incidence of a plane wave on a flat surface, we can show that the normalized acoustic impedance ratio, ζ_o, is related to the absorption coefficient by:

$$\alpha = 100 \quad \frac{4 \, | \zeta_o |}{| 1 + \zeta_o |}$$

If the acoustic wave is incident at an angle other than 90 degrees, the acoustic absorption coefficient may be different from the value computed from ζ_o.

Two examples of this difference may be cited. In the first, we found that the acoustic absorption coefficient was lower for random incidence than for normal incidence. This result was obtained on a dense fiberglas sample. A 2-inch thick cylinder of fiberglas was placed at the sample end of our impedance tube (ref. 8). We found that the absorption coefficient as measured by the impedance tube was greater than 95 percent in the range of 2-9 kc and dropped rapidly as the frequency was lowered below 2 kc. In the large reverberation chamber (described in the next Section), it was possible to repeat these measurements on a larger piece of the same fiberglas block. Here we found that the absorption coefficient was also independent of frequency above 2 kc and dropped precipitously below 2 kc. But the absorption coefficient in the reverberation chamber was only about 70 percent of that

in the impedance tube. This difference was not due to the sample size differences. Various sizes were tried in the reverberation chamber. If too large a sample was used the computed absorption coefficient depended on the sample size. However, below about 150 cm^2, the measured absorption coefficient was independent of sample size or shape. Thus the factor of 0.7 between the measurements in the impedance tube and the reverberation chamber must have been due to the difference in incident sound waves. In the impedance tube one uses normally incident plane waves of a single frequency, whereas in the reverberation chamber random incident noise of a narrow (1/3 octave) bandwidth is employed.

If one were willing to stop here one would conclude that absorption coefficients measured for normal incidence were always higher than those measured for other angles of incidence of a plane wave. This however would be a false conclusion for other examples exist in which the opposite is true. Consider for a moment the case of a thick steel panel. If one measures the density and the speed of sound within this panel, one may compute its characteristic impedance

$$\rho c \doteq 4 \times 10^6$$

and hence for normal incidence, its normalized impedance ratio:

$$\zeta_o = \frac{\rho c}{(\rho c)_o} \doteq 10^5.$$

Referring back to the formula for the absorption coefficient, one finds readily that

$$\alpha \doteq 4 \times 10^{-3} \%.$$

If one tries to put a solid piece of metal at the end of our impedance tube, one finds that the absorption coefficient is not so small at all. Rather we have found typical values in the range of 1 to 3 percent. In the large reverberation chamber we have also found average absorption coefficients for the walls in this general range. In spite of this, there can be no doubt that the computed value above must be the correct value for the case of normal incidence of a plane wavefront of infinite extent on an infinitely thick piece of metal.

Some insight as to the reason for failure of the above computed value for the absorption coefficients for metals to fit our measured values can be gained from the following example. It is possible in any known metal panel, or finite piece of metal, to excite various surfaces, and shear waves. For some panels these transverse waves will have a wavelength comparable to that of sound waves. At a given angle of incidence there are some frequencies which will pass through the panel with close to one-hundred percent transmission. More complex theoretical treatments have predicted these results and experiments have confirmed the theoretical studies. Although it does not seem reasonable to expound on these here, we should point out that were this panel a part of one side of a reverberation chamber and were it backed with fiberglas we would find a very high absorption coefficient for the panel

perhaps in the 10 or 15 percent range at some frequencies. Accordingly the reverberation data for random incidence may be expected to show a higher absorption than that for normal incidence in some cases and a lower value in others.

The dependence of the absorption coefficients on the geometry of the incident sound field is emphasized by the experiments referred to earlier (refs. 2, 3, 4, 5, 6, 7). Some of the various rods and modified impedance tubes were placed against parts of the human body surfaces. At any given frequency, the absorption coefficient measured decreased with increasing rod or tube diameter. It is also clear that the greater number of wavelengths in diameter the incident sound field has, the less the probability of exciting surface waves. As the frequency is increased for a given tube or rod, the diameter in wavelengths also increases. This qualitatively leads us to expect a decrease in absorption with increasing frequency for any given rod or tube. Detailed theoretical studies by Oestreicher et al (ref. 9, 10) have predicted essentially this result.

To return to metal, the above observations suggest that due to the fact that the impedance tube has a finite diameter, transverse waves are excited in the metal. Likewise, the high absorption coefficient of the reverberation chamber walls, as compared to the computed value, is probably due in part to the excitation of transverse waves. It is also probably due in part to the inequality of excitation forces resulting from clamping the metal at its edges. Finally the finite thickness of the metal can give rise to complex interference patterns which may alter its acoustic absorption coefficient.

In the case of human body surfaces, the surface and transverse waves will be more highly damped than in a metal at corresponding frequencies. These waves in humans also will be exited by waves at other than normal incidence or unequally distributed over the limb. For an arm or leg, as the frequency is raised the variations in sound pressure around the limb increase. Thus one would expect surface waves to be more readily excited due to this change. On the other hand, the ability of a given pressure difference to excite these surface waves has been shown to decrease as the frequency is raised. Thus it seems not unreasonable to guess that the absorption coefficient for an entire limb in a randomly oriented sound field will not depend critically on the frequency over quite a wide range. At low frequencies, below 1 kc, the reports referred to earlier strongly indicate that the absorption coefficient will rise due to the excitation of surface waves which actually become visible below 100 cps. The data presented in this report indicate that the average acoustic absorption coefficient will remain approximately constant from 1 to 20 kilocycles.

SECTION III

EQUIPMENT

The equipment used was similar to that described in a previous report (ref. 1), in the section on the asymetrical reverberation chamber. A block diagram

reproduced from that report is shown in Figure 1. Basically this equipment measured the time for a drop in the sound pressure level within a reverberation chamber of 30 db. One-third octave bands of noise were used. The reverberation chamber used initially also was described in the previous report and is reproduced here as Figure 2. This chamber was used to measure acoustic absorption coefficients for human hands, fingers, and palms, as described in the next section.

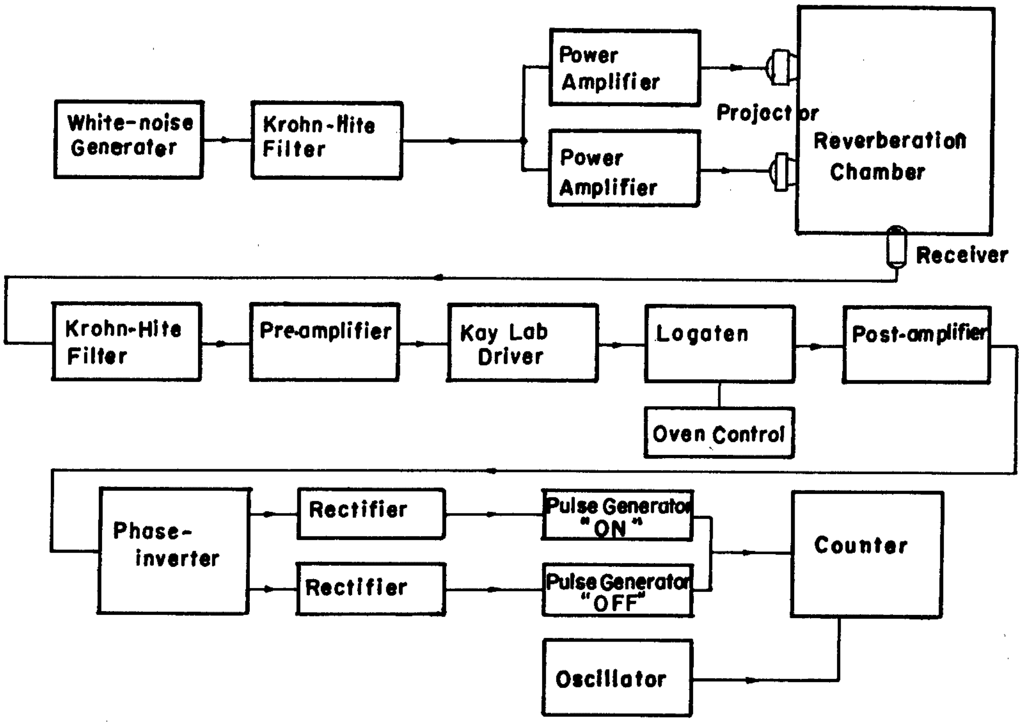

Figure 1. Block Diagram of the Apparatus

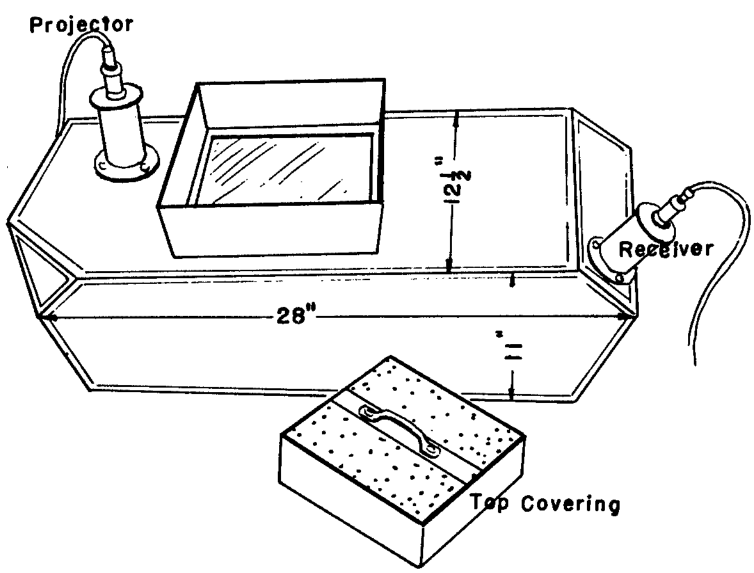

Figure 2. The Smaller Reverberation Chamber

Neither the volume nor the linear dimensions of this chamber were of such a nature as to make it convenient to insert an entire limb. Accordingly a larger chamber was designed. Its dimensions are shown in Figure 3. The larger chamber was built of 1/4-inch thick boiler plate. This proved far superior to the small asymetrical chamber which had about 1/16-inch thick brass walls. The walls of the small chamber vibrated and stored appreciable amounts of energy. The larger chamber did not suffer from these difficulties.

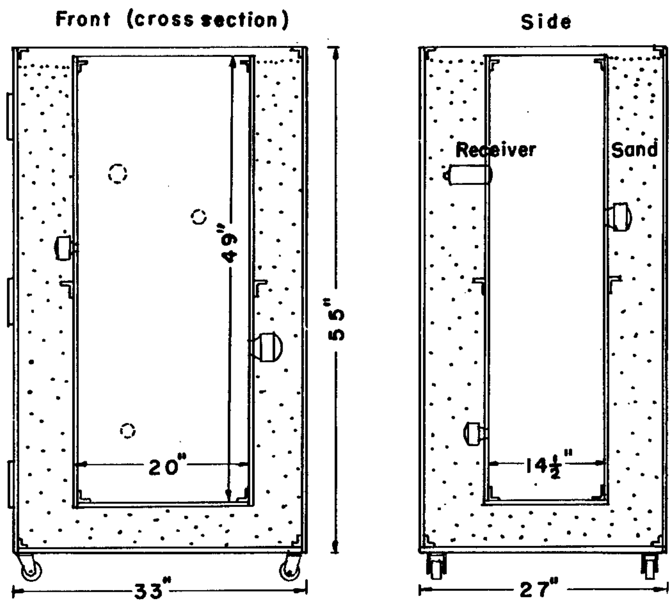

Figure 3. The Larger Reverberation Chamber

Four driver elements were used to excite the large reverberation chamber. These were driven by three 25-watt amplifiers. Several different types of tweeters were tested. Those finally used were two University B-35 units and two University Mod. MID-T 6-watt units. Likewise, several different microphones were tested. Finally an Altec Lansing Microphone was used. The Kay Lab preamplifier originally used proved too noisy and was replaced by a special preamplifier. The schematic diagram of the latter is shown in Figure 4.

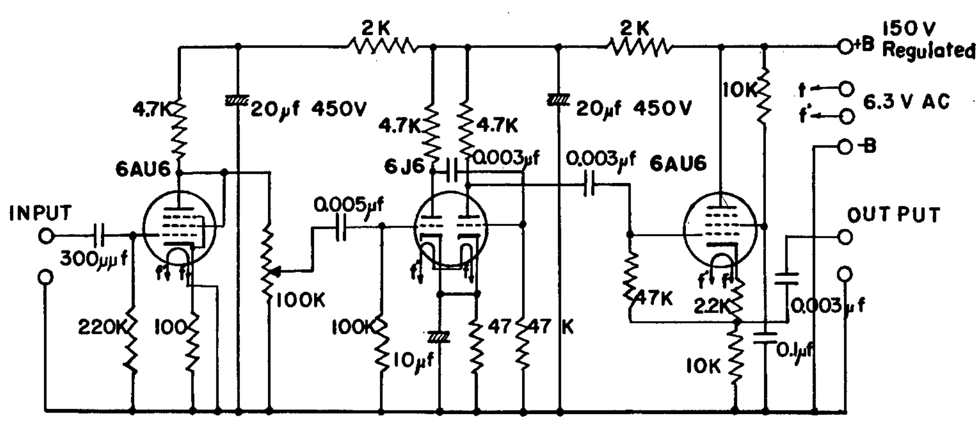

Figure 4. The Preamplifier

To check the performance of the large reverberation chamber, small microphones were placed in several of the available ports. As in actual use the large reverberation chamber was placed in an outer box and surrounded with sand. Measurements from 500 cps to 10 kc showed that the sound pressure levels were independent of position above 2 kc. Even down to 1 kc the variations with position appeared only slight. Moreover, the sound pressure levels appeared to depend only slightly on the location of the driver elements used.

As with the smaller chamber the decay of sound was checked to see if it were exponential in time. The output at the logaten (c.f. Fig. 1) was displayed on the oscilloscope and a straight line of at least 35-db decay was found from 1 to 10 kc. Above 10 and below 1 kc, the equipment could not be used.

The reverberation time measured is related to the total absorption by the well known Sabine Formula:

$$\tau = 1.45 \frac{V}{\alpha A} \cdot$$

Here, τ is the reverberation time in seconds; i.e., the time required for the steady-state sound energy to decrease by 60 db; V is the volume of the reverberation chamber in milliliters; A is the area of the absorbing material in square centimeters; and α is the absorption coefficient (absorption per unit area) of the absorbing surface. If more than one absorbing material is present, the total absorption αA is represented by the sum of the products of the individual absorption coefficients and their respective surface areas.

By taking the differences in absorption with and without a limb in the chamber, it was possible to compute the absorption due to the limb.

Both the smaller asymetrical and the larger chamber had to be encased completely in sand. If this were not done, energy fed through the side walls would contribute to the observed reverberation time in an uncontrolled fashion. Persons moving, noises, building vibrations would all alter the observed reverberation times. The sand in itself provided a difficult problem since a small amount of sand within the chamber altered the reverberation time more than a human limb.

The importance of a tight air seal also should be emphasized. To obtain reproducible results, even at 10 kilocycles, it was necessary to guard against any air leaks. Originally, Dr. Robert L. Berger made a special metal cuff held on to his wrist by tape, which fitted into a special lid for the small asymetrical chamber. This proved to be completely worthless. The exact nature of the seal, and the tape holding the metal to the skin, and the air leaks completely determined the apparent absorption coefficients. These values moreover were completely irreproducible.

Several additional attempts to make an iris-type diaphragm all met with similar failures. Different thicknesses of metal, different packing around the hand, the use of plasticene all gave irreproducible results. Finally, we ended up making

separate holders for each hand, each finger, and for arms and legs. One of these is sketched in Figure 5.

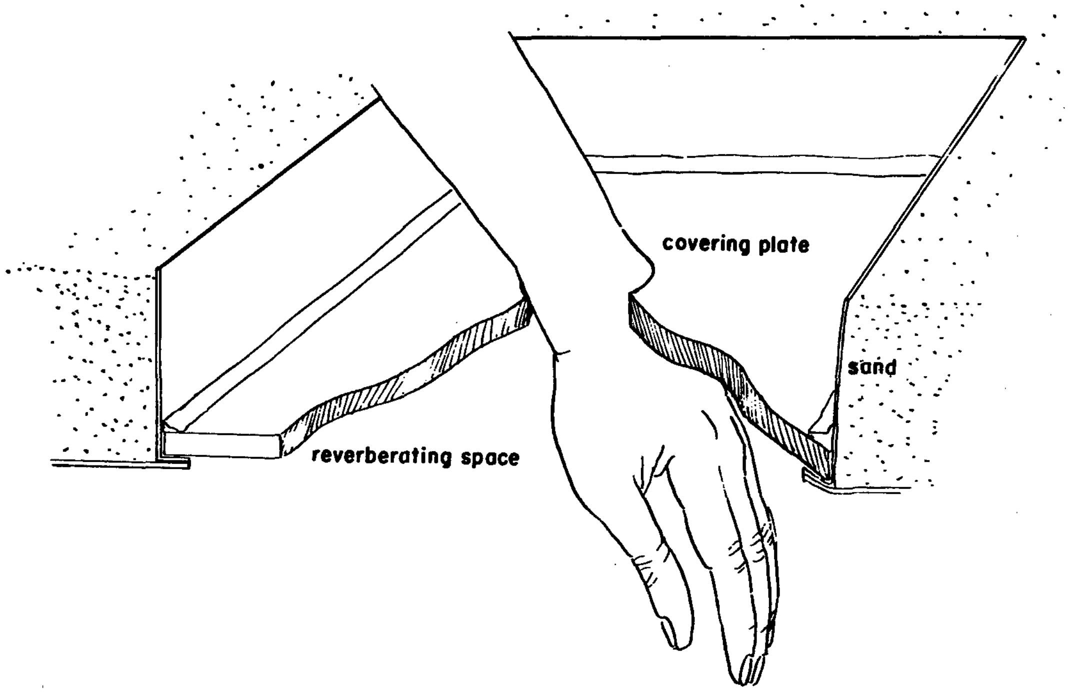

Figure 5. Sketch of Hand and Hand Holder

The hand holder for the small asymetrical chamber was made by first replacing the removable lid, with a similar sand filled lid except that a cylindrical tube, about 5 inches in diameter, was placed down through the sand. The bottom of the tube was removed, leaving a circular hole. Before putting on this cover, a flat galvanized iron sheet and a flat cardboard sheet were placed over the chamber opening. The galvanized iron sheet had a circular opening, slightly larger than a concentric circular opening in the cardboard. The opening in the cardboard had a sufficient diameter so that the hand could just fit through with the fingers curled. It was small enough so that it stopped the forearm, just above the wrist. Different holders were necessary for each person.

For measurements with single fingers a similar arrangement was used. However, the cardboard was omitted. The opening in the galvanized iron sheet was so small that the hand was stopped at the base of the finger used. By pressing hard, an airtight seal could be made just as in the case of the hand holder.

The 5-inch diameter lumen in the sand filled top was too small to be closed by the palm of a hand spread out flat. For measurements on the human palm, thick galvanized iron and aluminum sheets were used. These were sealed with plasticene to the chamber and covered with sand-filled, plastic sandwich bags. The sand bags were arranged to cover the hand (or metal standard) as well as the remainder of the sheet.

Finally, data were obtained on the absorption of whole arms and legs. For the latter studies, two special holders were designed to cover the large chamber. These holders were made from 1-inch thick aluminum; they were sealed with plasticene around the edges to the large chamber. When the limb was inserted, the body sealed against the specially shaped edges of the hole. A flat aluminum lid, also 1 inch thick, was used to cover the hole for the standard when the limb was removed. The seal around the lid was made air-tight by a thin rim of plasticene around the opening in the holder.

In spite of all these precautions difficulty was still experienced at 1 kc in obtaining reproducible results. The crux of the difficulty seemed to be that there were not enough resonant frequencies near 1 kc to justify the use of the Sabine Formula. Accordingly the measured absorption at 1 kc was sensitive to the position of the limb. Some difficulties of a similar nature were also experienced at 1.5 and 2 kc; these were "cured" by hanging two metal radio chasses within the chamber. The chasses apparently broke up the predominant standing waves.

The sound level in the large reverberation chamber was in the neighborhood of 120 db whereas the level in the small asymetrical chamber was 80 to 100 db. A comparison of the absorption coefficients measured in the two chambers was useful in evaluating possible nonlinear effects.

SECTION IV

DATA

A. Hand and Forearm

A large amount of data was accumulated using various people's hands in various holders. All of these proved to be functions primarily of the holder used. In an effort to improve the equipment, the sand was repacked under and around the asymetrical chamber. This eliminated most of the resonances of the chamber walls; it made unnecessary the calibration in terms of fiberglas used with the laboratory animal experiments.

Finally the holders described in the previous section were constructed and data were obtained using the hands and forearms of three subjects. No consistent trend with frequency could be found from 1 to 20 kc. The values of the acoustic absorption coefficients are presented graphically in Figure 6. No consistent difference exists between the three sets of values although one subject had very hairy hands and another subject had almost hairless hands.

Additional experiments ruled out a number of other possible variables. The position of the hand had no effect on the results. The position of the fingers relative to one another likewise did not alter the measured absorption coefficient. In the final computation, the decrease in volume with the hand inserted as well as the decrease in wall absorbing areas were both included to increase the precision of the results.

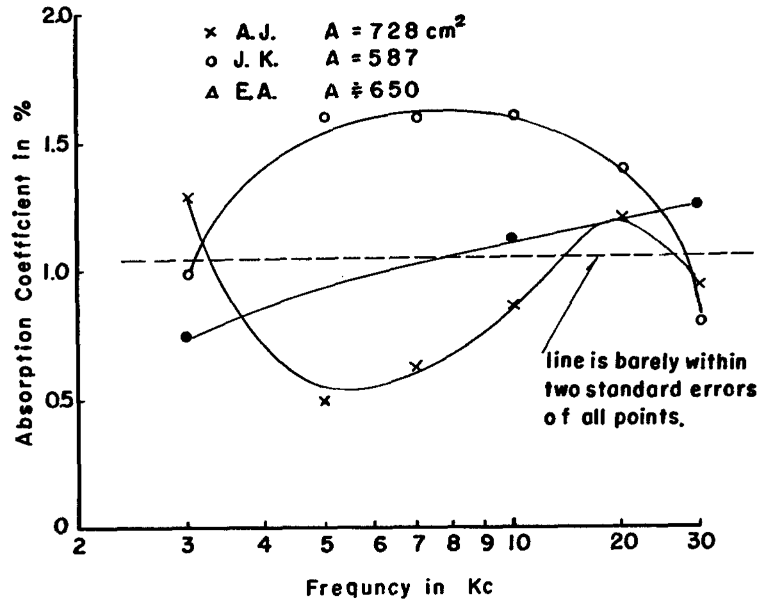

Figure 6. Acoustic Absorption Coefficients of the Surfaces of Human Hands and Forearms

The differences in the reverberation time due to the presence of the hand and forearm were small. Although the differences in the values, for 25 determinations each, were statistically significant, a total of at least 150 determinations per hand were made at each frequency. This reduced the experimental error. To eliminate the influences of sand, instrument drift, room temperature fluctuations, etc., we took a set of 25 determinations of the reverberation time with the hand and forearm in the chamber and then a set of 25 determinations with the empty chamber sealed by a metal block or other suitable object. Further, we attempted to run through the entire frequency range each time rather than accruing a large number of measurements at one frequency on any one day.

B. Fingers

Similar, but much less extensive data were obtained using fingers. Complete data were only taken for one finger. The technique used was the same as that for the hands and forearms. The fingers, being smaller, needed smaller holes in the holders. The smaller size meant that the absolute errors were very great. The data using a single finger indicated a decrease in absorption coefficient with increasing frequency. The errors, however, were so large that this decrease is hard to distinguish from statistical fluctuations.

C. Palm of Hand

The palm of the hand was placed over an opening in the top of the chamber. Thus we really measured the difference between the absorption of the palm and that of an equal area of metal. Various shapes, various metal surfaces, and various

thicknesses were used. In spite of this the absorption of the palm was consistently less than that of the metal walls of our chamber above 5 kc. For a long time we refused to believe the data. Gradually, we realized that the palm did absorb less than the metal walls. The data of von Gierke for flat surfaces also predicted that the palm should absorb less than the measured average wall absorption of our chamber.

Tests were made on hands of five different people. All showed that the absorption of the palm was close to that of the metal. In fact, with 25 determinations at each frequency, only the measurement at 20 kc showed a significant difference between the palm and the metal. Accordingly a set of five-hundred determinations were carried out at each frequency with and without the palm in place. These gave statistically significant greater absorption for the palm at 3 and 5 kc and significantly less for the palm at 7, 10, and 20 kc. Data at 15 kc indicated that the two were the same within the limits of error. In order to avoid any personal bias in interpreting these data, they are reported in Figure 7 as differences between the absorption of the palm and of the metal in the side of the asymetrical chamber. The general trend of the data is towards smaller absorptions at higher frequencies if the absorption of the chamber is constant. For reference purposes, the average absorption of the chamber is also included in Figure 7. The absorption coefficients of the metal standards used for the palm hole obviously may not be the same as the average for the entire chamber.

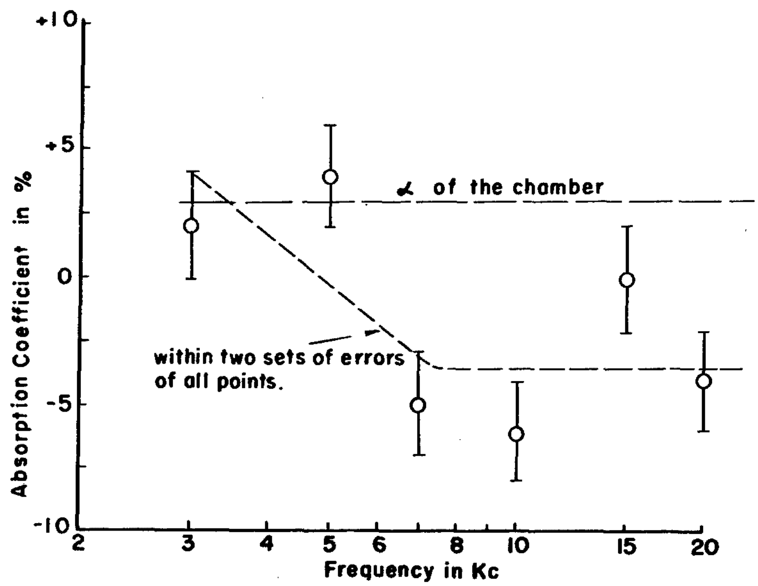

Figure 7. Acoustic Absorption Coefficients of the Surfaces of Human Palms. Data are Difference between Palm and Chamber Wall

D. Arms

The absorption coefficients for two arms were measured in the large chamber; the results are summarized in Figure 8. These data are by far more pleasing than the palm or finger measurements in that 50 determinations were statistically significant. With sufficient care to have air-tight seals the values were reproducible within the limits of error. These values are close to those obtained for the

hand and forearms. Since the chamber was sufficiently large, no corrections were introduced for the change in volume with the arm in place. Also, no correction was introduced for the decrease in the area of the chamber walls. These two would probably cancel each other without corrections.

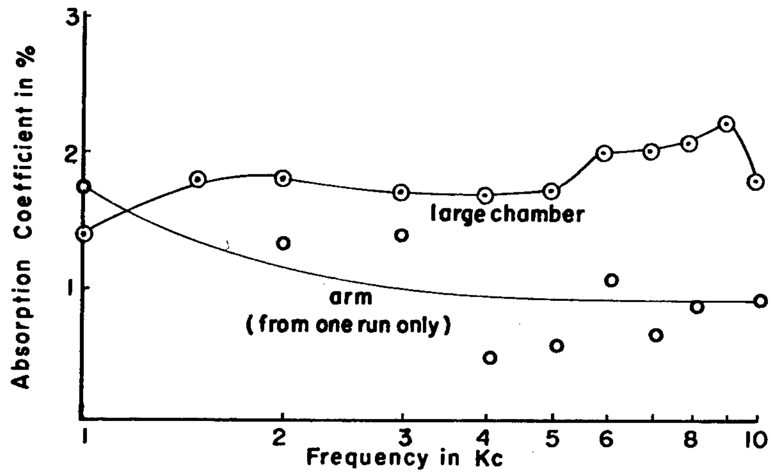

Figure 8. Acoustic Absorption Coefficients of the Surface of Human Arms

E. Legs

The entire leg was inserted into the large chamber. Data obtained were similar to those for the arm. These showed that our measurements were not uniquely dependent on the particular limb used. The absorption coefficients measured for bare legs are shown in Figure 9.

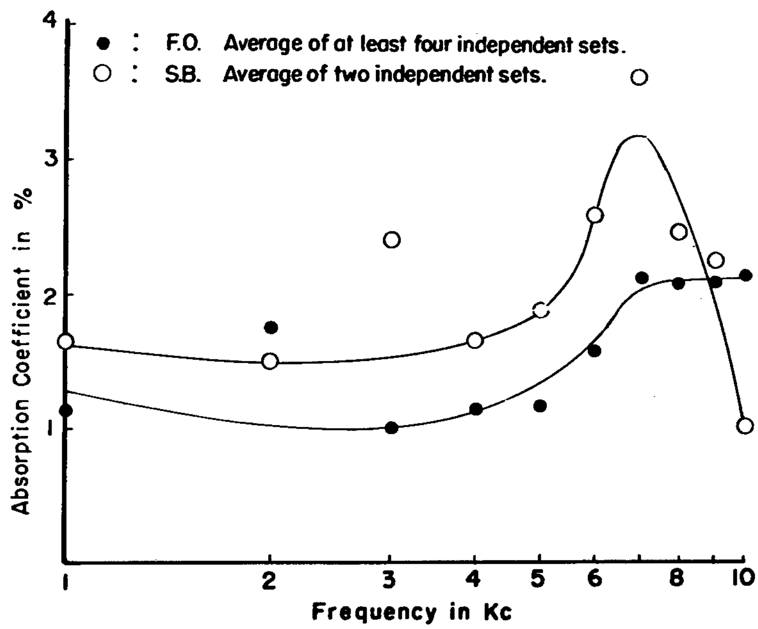

Figure 9. Acoustic Absorption Coefficients of the Surface of Human Legs

F. Clothing

No extensive data were taken with clothed limbs. However, on many spot checks we found that any type of cloth available had an absorption coefficient which was many times that of the human skin.

SECTION V

SIREN MEASUREMENTS

A few measurements were made using the siren. We confirmed that from 18 to 30 kc a human hand did not rapidly absorb appreciable amounts of energy except when the fingers were close together. This is discussed further in the next section. We also exposed several palms at about 25 kc and 165 db free field sound pressure level to the center of the siren beam for 5 to 7 minutes. In each case, there was no sensation for the first 3 minutes. Thereafter, an intense pain developed, not at the outer surface, but rather at the surface of the bone. Some discomfort was felt even 4 days later. Thus a severe heating appears to have occurred at the bone-tissue interface.

SECTION VI

DISCUSSION

A. Miscellaneous Notes

Several aspects of the previous data should be noted. The first is the similarity of the acoustic absorption coefficients for human limbs in a randomly oriented sound field with the corresponding coefficients for the metal surfaces in our chamber walls. These values, lower in some cases than the acoustic absorption coefficients for metals, make it clear that the human body will reflect most of the incident sound energy.

Second, one should note that the formula for normal impedance for a plane wave of infinite extent cannot be applied to human surfaces. The shape, both of the object and of the sound field, will alter the observed absorption coefficient. Two extreme cases are possible. One is to choose small flat parts of a limb and use a plane wave at normal incidence. The other is to use an entire limb and use a large number of waves at random angles of incidence. The first case was the situation employed in the measurements described in (refs, 2, 3, 4, 5, 6, 7). The second was used in many of the measurements reported here. It would be indeed surprising if both of these gave either the same absorption coefficients, or completely different orders of magnitude for the absorption coefficients. A comparison of the data shows that the absorption coefficients measured by the two methods agree within a factor of about 10, but disagree in actual magnitude or frequency dependence.

The measurements reported of the acoustic absorption coefficient of the palm of the hand lie in between the two extreme cases described in the last paragraph.

Here the area used was flat (or in one individual, flattened with weights) but the sound fields consisted of randomly incident noises. The measured absorption coefficients also lie in between the two extremes, in the nature of their frequency dependence.

Our measurements showed that at sound pressure levels as high as 130 db, no noticeably nonlinear effects occurred in the absorption of sound by human body surfaces. On the other hand at 165 db, nonlinear effects do occur, as represented by the rapid heat development between the nearly closed fingers in the siren sound field. Even this is not a nonlinearity of tissue absorption, but rather of the sound field in air.

B. Distribution of Absorbed Energy

One important question is not answered by the experiments discussed in this report; "what happens to the sound energy absorbed?" In the case of haired laboratory animals or absorbent cotton, it is converted into heat in the small pores between the hairs or fibers. The hair on a human head might show a similarly large absorption of sound energy, although we have not tried this. In the case of a hairless mouse, our experiments (ref. 1) have shown that the sound energy absorbed is converted into heat in the outer skin layer. Does this happen to humans also? We cannot say except to note that human skin is attached much more tightly to the underlying tissue than is the skin of a rodent. This suggests that the energy is distributed over a larger volume before it is dissipated as heat.

When hands are placed in the siren sound field at 20 kc, our experiments suggest that heat is eventually developed at the bone-soft tissue interface. This effect is well known in ultrasonic diathermy and is the limiting factor in the rate of heating advisable. Since the hand is such a good reflector in the audible and low ultrasonic range, the sound pressure level directly before the hand will be 6 db higher than the free field value.

That is to say, for a free field sound pressure level of 165 lb., the pressure level just in front of the hand would be about 171 db. Since the acoustic pressure is continuous across the air-tissue interface, the sound pressure level within the skin would also be about 171 db. Moreover, the bone reflects most of the sound energy reaching it from the soft tissues so that the sound pressure level at the surface of the bone could approach 177 db even though the free field pressure level was only 165 db. In other words, although the intensity has dropped almost to zero, the sound pressure level at the surface of the bone may be 12 db higher than the free field value. In a highly focussed sound field as that of the siren it is possible that this difference in levels exceeds 12 db.

C. Estimates of Thresholds for Heating

In considering possible harmful effects of intense sound fields on humans, it is instructive to compare the results for hairless mice with those for humans. At 6 kc the absorption coefficients for random incidence are comparable. In a siren sound field at this frequency the hairless mice were heated but not killed at a free

field intensity of 165 db. However, the volume to surface area ratio is greater for a human than a mouse. Since the energy absorbed depends on the surface area, while the heating depends on the heat capacity (which is proportional to the volume), a higher intensity is necessary to heat humans at a comparable rate.

The necessary increase can be estimated as follows. By and large, the volume to surface ratio increases as the cube root of the ratio of the masses of different animals. The hairless mice weighed around 25 gm and a typical human weight is 70 kg; the ratio is about 3×10^3. Hence, humans will have about 10 times the volume to surface ratio. In other words, humans would be heated at a free field sound pressure level around 175 db, provided all the body except the hair is exposed to the sound field. This should be true if the sound energy is in the 1-to 20-kc range. This general range is in agreement with previous calculations (refs. 3, 4). However, this overall heating should not cause any irreversible damage. In addition sweating increases time of heating as well as threshold.

If clothing of any type is worn, the absorption of sound energy by the clothing is far more important than that absorbed by the bare body surfaces. No measurements were made to compare different types of clothing.

If sound energy at 20 kc is absorbed primarily at very thin layers, it is possible for appreciable damage to occur at incident sound pressure levels below 175 db and considerably less than total body exposure. Suppose the incident sound is at a free field sound pressure level of 166 db. This means that 2 watts are incident on each square centimeter. An absorption coefficient of 2 percent corresponds to a rate of heating of 0.04 watts, a negligible amount for a whole hand. If, however, all of this power is focussed into a smaller area, and absorbed in a very thin membrane at the bone surface, it may represent an appreciable heating rate at that surface. Our experiments in the siren sound field above 20 kc indicate that destructive heating at the bone surface may be a real possibility even though only small areas are exposed.

In the case of hairless mice, most of the energy appears to have been absorbed at the skin. In human subjects also possibly the skin is a major contributor to the acoustic absorption. No direct experiments have been conducted to check this possibility, but it is anatomically unlikely. Furthermore, theoretical calculations, based on the assumption that local skin absorption is unimportant, were successful in predicting the absorption coefficients measured by the rod and impedance tube methods (refs. 3, 4).

No experiments have been conducted to determine the acoustic absorption coefficients above 20 kc. There seems little doubt that the coefficient for normal incidence on a restricted plane area will continue to decrease as the frequency is raised. But there is no reason to suspect that the absorption coefficient for random incidence on an arm or leg should behave in a similar fashion.

SECTION VII

SUMMARY

The acoustic absorption coefficients for the surfaces of human hands, fingers, palms, arms, and legs have been measured using reverberation type techniques. The frequency range 1 to 20 kc was studied. All data indicate that these absorption coefficients are in the order of 1 percent. The data for hands, arms, and legs show a different frequency dependence than do the data for normal incidence of plane waves on a flat human surface. This difference appears due to the nature of the wave pattern excited. The absorption of the palm is between these two extremes. The measurements are all in qualitative agreement in this frequency range.

Calculations, based on the measured acoustic absorption coefficients, show that for whole body heating of an unclothed man in a free field intensity of at least 170 db would be necessary. Any type of clothing would absorb more energy than the body; dissipation of its heat is a more significant problem than the overall direct heating of the body. However, if sound energy is absorbed in small volumes at the surface of the bones, it is possible to obtain heating at lower sound pressure levels. Siren experiments have suggested this possibility in the neighborhood of 20 kc.

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Unclassified report

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